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SUMMARY

The average charge-to-mass ratio of submicron carbon powder charged in a parallel plate system was determined by using a quadrupole mass filter, which permitted coverage of the range from 10^{-3} to 10^{7} coulombs per kilogram. A high intensity, low charge-to-mass ratio peak and several low intensity, high charge-to-mass ratio peaks were found. The average charge-to-mass ratio was about 10^{-1} coulomb per kilogram for an applied field of 10^{5} volts per meter. Results were compared with theory. Extrapolating these results to obtain an estimate of the effects of a field of 10^{7} volts per meter indicated that unreasonably high accelerating potentials would still be necessary to obtain useful specific impulses for colloidal thrustors.

INTRODUCTION

Electrostatic colloid thrustors offer the theoretical advantage of high overall efficiency at low specific impulse levels (ref. 1). The effective use of colloidal particles as a propellant is contingent upon several factors, among which are requirements for a reliable and simple method of particle preparation, a sufficiently narrow charge-to-mass distribution, a high utilization efficiency, and an average charge-to-mass ratio of 10^{3} coulombs per kilogram or greater. The last of these conditions is needed to attain specific impulses in the range of 2000 to 10 000 seconds. Preformed colloidal particles have appeared attractive as a propellant because they can be produced with acceptable unagglomerated mass distributions and sizes; consequently, onboard equipment may not be necessary for particle preparation. This advantage, coupled with a high power efficiency, can result in a thrustor system with a high overall efficiency with acceptable voltages (e. g., less than 500 000 volts).

Because of their large mass, particles of micron size cannot easily be charged to the required charge-to-mass ratios. However, submicron sized powders, which have recently been produced by modern technology (ref. 2), may possibly be charged to the proper charge-to-mass ratio. The submicron powder may tend to agglomerate rapidly because of the London - van der Waals attraction forces (ref. 3); however, as will be discussed later, some agglomeration may be acceptable. Many previous investigators in this field have been limited to some extent by the available size range of preformed powders (refs. 4 to 9). Various methods were used to contain the powder, to break up the agglomerated powder, and to charge the resultant particles. These previous studies did not cover the entire charge-to-mass range needed for complete analysis of the exhaust beam. It would be expected, particularly with agglomerated submicron powders, that a wide charge-to-mass ratio range might be possible.

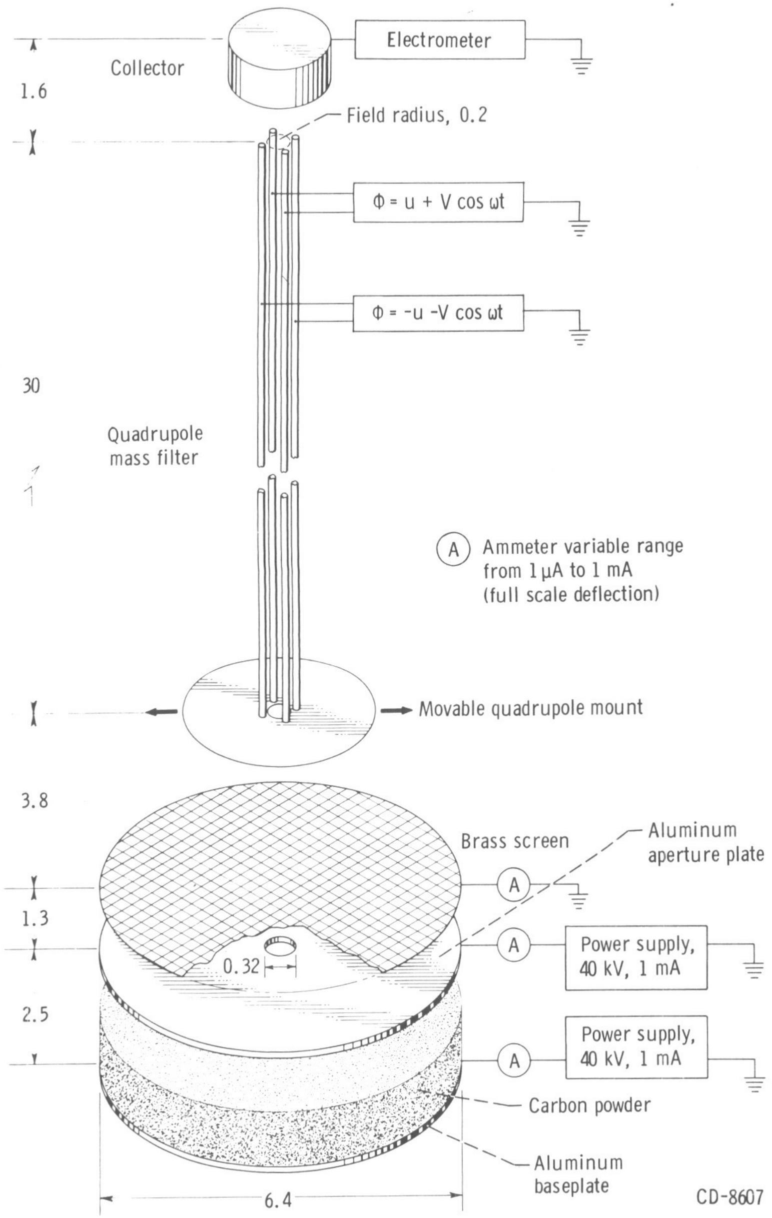
Both the time-of-flight spectrometer and the quadrupole mass filter have been used extensively in other colloidal beam analyses. The operating characteristics of the time-of-flight spectrometer permit only gross determination of the charge-to-mass ratio spectrum (ref. 10). The quadrupole mass filter, however, is theoretically capable of analyzing a much broader charge-to-mass ratio spectrum (ref. 11).

In this investigation, submicron powder with an unagglomerated mean size of 0.007 micron was used in conjunction with a simple parallel-plate contact-charging system. The resultant beam was analyzed with a quadrupole mass filter.

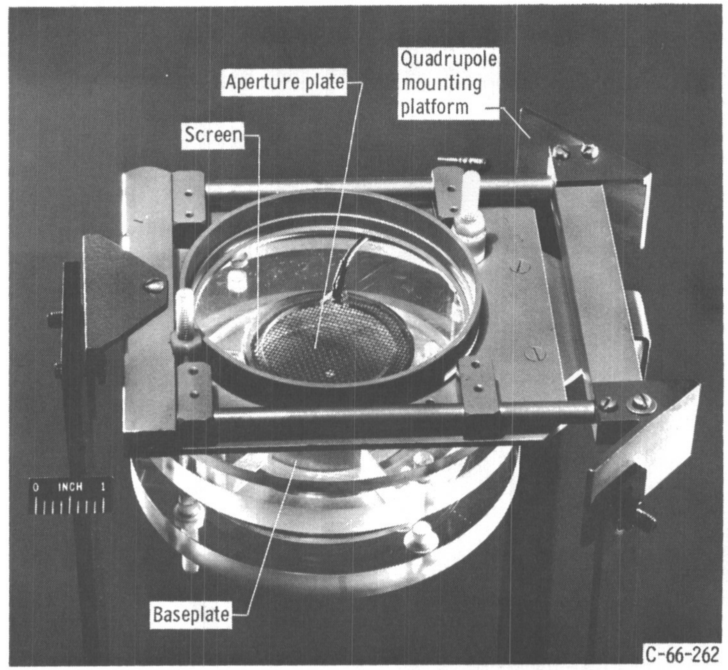
APPARATUS AND PROCEDURE

Colloidal Particle Charging Chamber

A schematic diagram of the experimental apparatus is shown in figure 1(a). Figure 1(b) is a photograph of the colloidal particle charging chamber mounted on a movable platform. The charging chamber consisted of a parallel plate arrangement in which two aluminum electrodes, a baseplate and an aperture plate, were separated by a cylindrical glass spacer. A circular hole, centered in the aperture-plate electrode, provided the exit opening for the charged beam. A 16-mesh brass-screen electrode was situated above the aperture plate to provide an auxiliary accelerating region. The screen electrode was separated from the aperture plate by a cylindrical glass spacer. Prior to operation, carbon powder was loaded into the charging chamber. The powder was then stirred gently in an attempt to break up some of the interlocking mechanical bonds between agglomerates. The entire system was mounted in a bell-jar type vacuum facility evacuated by a liquid-nitrogen-cold-trapped 6-inch oil-diffusion pump. Electric potentials were applied to the charging chamber as shown in figure 1(a). The screen was maintained at ground potential and the other electrodes could be maintained at either high positive or



(a) Schematic of powder charging apparatus and quadrupole mass filter.



(b) Powder feed system.

Figure 1. - Experimental contact charging system. (Dimensions in centimeters.)

negative potential with respect to ground. The charged-particle mass-flow rate was determined by both the voltage applied across the charging chamber and the diameter of the aperture hole. It was found in preliminary tests that a 3.2-millimeter-diameter hole in the aperture plate provided an adequate propellant mass flow rate for beam analysis over the range of voltages employed. Also, these tests indicated that a 13-millimeter-long glass spacer was adequate to avoid coating the auxiliary section with carbon, which could lead to electrical breakdown.

Outgassing of the carbon powder was observed during the initial pump-down phase, and when the outgassing was allowed to proceed at too high a rate large quantities of powder were expelled from the charging chamber. Pumping down the system slowly to 10^{-1} torr alleviated this problem. Final operating pressure in the facility ranged from 10^{-6} to 10^{-5} torr. The applied field across the charging chamber was maintained at about 10^5 volts per meter. The effect of this field was to cause the powder to oscillate in the gap between the base and aperture electrodes. This phenomenon is explained as follows: Under the influence of the applied field, the carbon powder in contact with an electrode became charged positively or negatively, depending on the direction of the field at the electrode surface. Electrostatic forces then accelerated the charged powder across the gap. Upon reaching the opposite electrode, the charge on the particles reversed polarity, and the powder was accelerated back across the gap. With each oscillation a fraction of the charged powder escaped through the exit aperture and was further accelerated to ground potential. In this manner a beam of colloidal carbon particles was provided for quadrupole analysis.

Quadrupole Mass Filter

The quadrupole mass filter is shown in figure 1 and described in detail in reference 12. Essentially it consisted of four cylindrical rods equally spaced about a 2-millimeter-radius tangent circle. In operation, radiofrequency voltages and direct-current voltages are applied to opposite pairs of rods to establish the electric field re required to stabilize the trajectory of a particle with a particular charge-to-mass ratio. A portion of the charged beam enters the quadrupole, and particles with stable trajectories traverse the length of the quadrupole to the collector. The collector consisted of a Faraday cage with a titanium honeycomb surface. The current was monitored by a vibrating reed electrometer. By systematically varying the frequency of the radiofrequency voltage (for fixed rf and dc voltages), it was possible to scan a charge-to-mass spectrum from 10^{-3} to 10^7 coulombs per kilogram. An X-Y recorder was used to trace the collector current as a function of frequency.

In the tests the quadrupole radiofrequency voltage was held constant at a value of

1000 volts. The frequency was varied from approximately 1 kilocycle per second to 10 megacycles per second to provide the full spectrum scan. The quadrupole resolution (a function of the dc and rf voltage ratio) was held constant at a value of 10, and under these conditions charge-to-mass ratios could be determined to within about 5 percent of the true value.

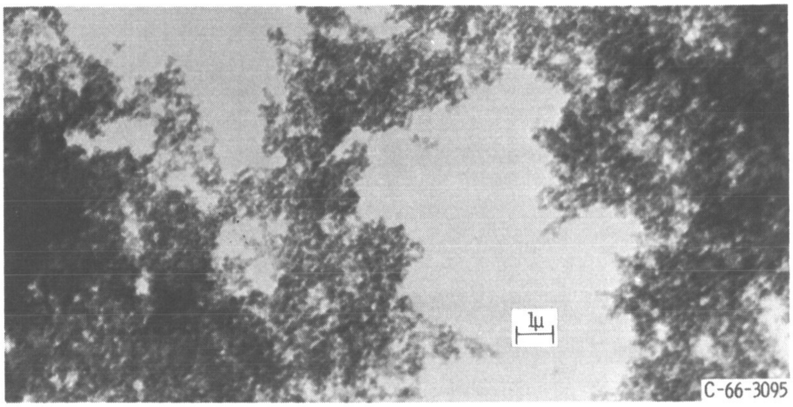
RESULTS AND DISCUSSION

Preliminary Analysis

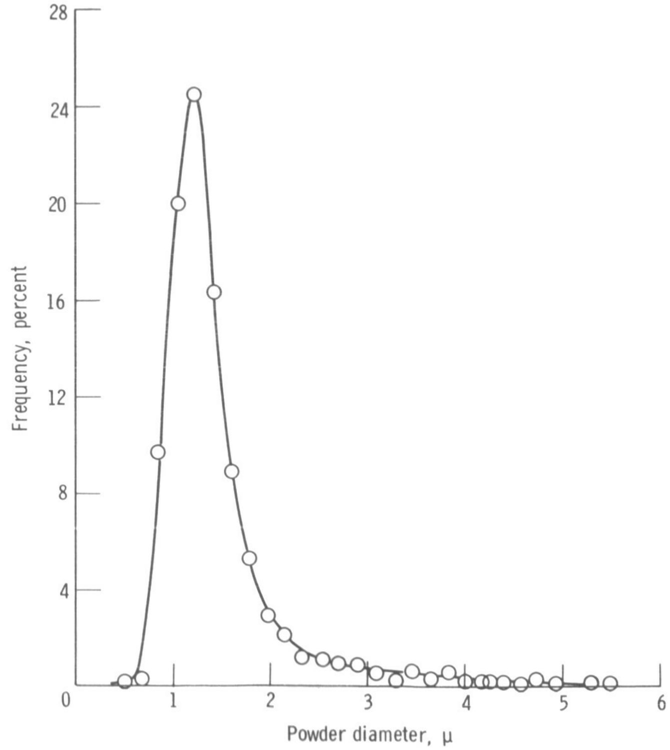
Powder. - An agglomerate is an assembly of many particles that are held in contact with one another by interparticle forces, primarily by the London - van der Waals attraction force. Although this force has a relatively short range (of the order of atomic dimensions), an appreciable portion of adjacent surfaces can be within atomic spacing because of conforming irregular shapes. It is also possible that the cohesive forces binding the agglomerate may be enhanced as the result of electrostatic surface charges generated during handling or processing operations (ref. 13). For extremely finely divided powder of submicron size, the cohesive forces responsible for agglomeration can approach, as an upper limit, the forces giving rise to the tensile strength of the material (ref. 14).

The powder used in this investigation was carbon black with a mean unagglomerated diameter of 0.007 ± 0.003 micron. A photomicrograph, figure 2(a), taken with an electron microscope, shows that the carbon is agglomerated and that the shape of the agglomerates is nonspherical. These nonuniformities can be expected to magnify local surface electrical fields greatly, as will be discussed further. An optically determined size-spectrum, figure 2(b), indicates that most of the carbon powders are agglomerated to approximately micron size, if it is assumed that no peaks in size distribution occur below the resolution of the microscope, which was 0.5 micron. According to reference 15, it is unlikely that mechanical deagglomeration of the powder (e.g., by grinding techniques) could result in particle dimensions less than 1 micron. Some deagglomeration may be expected if electrostatic forces between the charges on the agglomerate overcome the attractive force between the particles. If such deagglomeration is possible, it can be shown (ref. 8) that the process should be essentially one of pulling individual particles from the agglomerate rather than of gross breakup of the total agglomerate. These ejected particles would be expected to have a high surface charge per unit area.

Powder charging. - In the present investigation, the carbon powder was charged by means of a contact charging process, which involves both induction charging and contact potential difference charging. Induction charging results from a large field intensity at the surface of the particle. As depicted in figure 3, when the carbon particle is placed



(a) Photomicrograph.



(b) Agglomerated distribution.

Figure 2. Submicron carbon powder analysis.

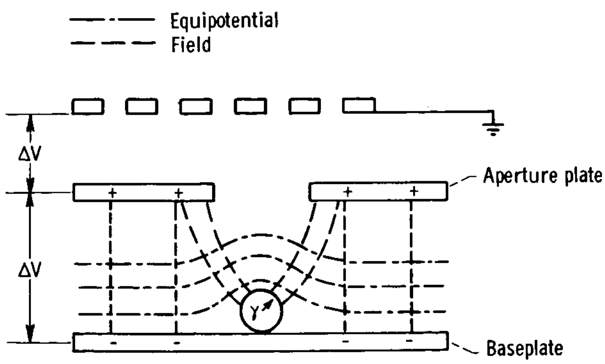


Figure 3. - Particle charging system.

on a baseplate electrode in a region of high externally applied electric field, the field will appear at the surface of the particle, which is regarded as being spherical. If the particle is in electrical contact with the electrode, as shown, electrons will be added to or drained from the particle, depending on the direction of the electric field. (The polarity of the particle charge will be the same as that of the baseplate voltage with respect to the aperture plate.) The magnitude of the induced charge q on a spherical particle, as a consequence of a uniform applied electric field E_0 in an infinite parallel plate system, has been shown to be (ref. 7)

$$q = 1.65(4\pi\epsilon_0 r^2 E_0) \tag{1}$$

(All symbols are defined in the appendix.)

Charging due to contact potential difference occurs between materials having different work functions. If the materials are brought into intimate electrical contact, so that their separation is comparable to interatomic distances, a free exchange of valence electrons can take place as a result of the wave mechanical tunnel effect within the region of contact (thermionic emission neglected). In the charging system under investigation, the carbon particles had only a limited opportunity to come into actual contact with the charging electrode. In general, the particles were in contact with other carbon particles where charging by contact potential difference would probably play only a minor role.

Additional charging considerations. - To determine the applicability of preformed powder to colloidal propulsion, it is necessary to examine the average charge-to-mass ratio and the charge-to-mass distribution function of the total beam. The average charge-to-mass ratio determines the accelerating potential required for a given specific impulse. For example, if 500 000 volts is taken as a reasonable upper limit for the accelerating potential, the average charge-to-mass ratio must be approximately 10^3 coulombs per kilogram to obtain a specific impulse of about 2000 seconds.

As particle diameters increase from submicron to micron, the number of charges per particle must necessarily increase to maintain the charge-to-mass ratio at a given value (e.g., 10^3 C/kg). However, the maximum number of charges that can be placed on a spherical conductor by any charging process is limited by the high electric fields formed at the surface of the particle because of the presence of these charges. These fields can cause field emission from negatively charged colloids and field desorption

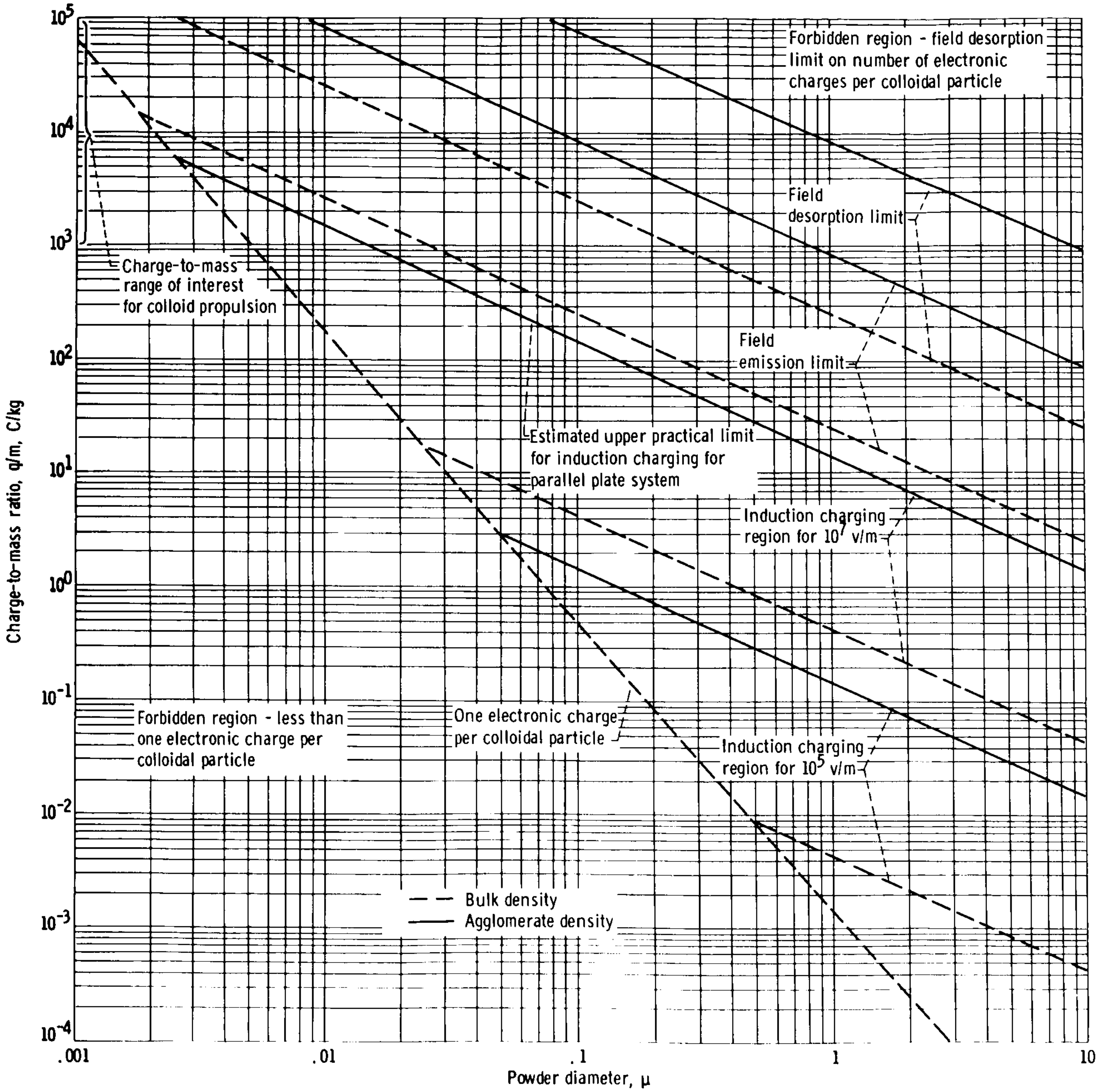


Figure 4. - Limits of induction charging of spherical carbon powder in parallel plate system.

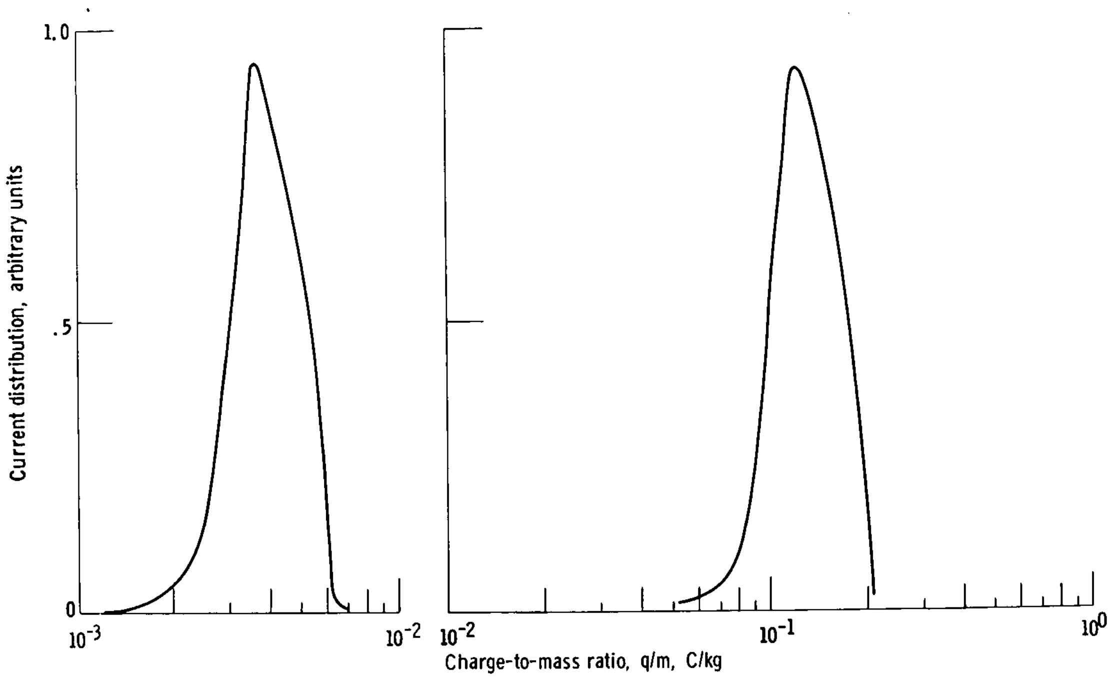
from positively charged colloids (e.g., emission of positive ions). Electron field emission occurs at a surface field intensity greater than 10^9 volts per meter (ref. 16). Positive ion emission, controlled by the binding forces of the atoms in the material, occurs at a field intensity greater than 10^{10} volts per meter (ref. 17).

Figure 4 shows a plot of the theoretical variation in charge-to-mass ratio as a function of carbon particle diameter for spherical particles. The range of interest for colloidal propulsion is given along with curves showing induction charging, field emission, and field desorption limits. Bounded ranges of the charge-to-mass ratio corresponding to the possible range of powder density are shown. For each applied field, the upper density limit is taken to be the bulk density of carbon (2 g/cu cm). The lower density limit is taken to be the density of the agglomerated carbon powder (0.06 g/cu cm). The latter density value is a measured value for agglomerated carbon powder. The true density, taking into account packing factors, would be expected to lead to charge-to-mass values falling below the charge-to-mass values calculated by using the agglomerate density, but above those calculated by using the bulk density. The maximum value of electric field for induction charging shown in figure 4 (10^7 volts/m) is based on experimental results for clean high-voltage parallel-plate systems (ref. 18), although electrostatic ion thrustors usually operate at fields in the low 10^6-volt-per-meter range.

The field emission and field desorption regions correspond to charge-to-mass values calculated from the maximum number of negative and positive charges, respectively, that may be placed on a spherical carbon particle by any charging process for the two extremes of density used. These regions correspond to the maximum upper theoretical limits on any charging process, providing density is taken into account.

As mentioned previously, a slight deagglomeration, leading to submicron particles of a high charge-to-mass value, can be expected as a result of electrostatic breakoff of individual particles. Also, from an examination of figure 2(a), it is evident the agglomerated particles are generally nonspherical in shape. The local field at the surface of a nonspherical particle can be slightly enhanced over the applied electric field (ref. 19). Field enhancement can lead to an increase in particle charge-to-mass ratios. These factors indicate that, at least theoretically, submicron carbon particles may give charge-to-mass values in the range of interest for colloidal propulsion.

Figure 5 shows the charge-to-mass distributions of the preformed carbon powder of figure 2(b), calculated by equation (1) for an applied field strength of 10^5 volts per meter. The effect of particle density is shown by comparison of figures 5(a) and (b). The peak charge-to-mass ratio increased as the assumed particle density was decreased.



(a) Bulk density. (b) Agglomerate density.

Figure 5. - Induction charging limits of preformed submicron carbon powder shown in figure 2(b), for an electric field of 10^5 volts per meter.

Experimental Results

Typical quadrupole traces obtained in the tests are shown in figures 6 to 8. The recorded quadrupole frequencies have been converted to charge-to-mass ratios in the figures. These traces also show the relative noise level of the system. In general, the traces were reproducible and show that high-intensity, low charge-to-mass ratio peaking occurred, accompanied by several low-intensity high charge-to-mass ratio peaks. In all cases, the major peak was obtained in the range from 10^{-2} to 10^{1} coulombs per kilogram and the low-intensity peaks occurred from 10^{1} to 10^{4} coulombs per kilogram.

Figures 6(a) to (d) show traces obtained at a constant field strength in the charging chamber of 10^5 volts per meter. Figures 6(a) and (b) show the effect of simultaneously varying the polarity of the baseplate and aperture plate voltages, while figures 6(c) and (d) show the effect of an accelerating-decelerating mode of operation.

In figures 7(a) and (b) the accelerating field, that is, the field between the aperture electrode and the screen, was the same. When the charging chamber field, however, was increased by a factor of 2, the beam intensity increased as shown in figure 8(b).

The traces presented in figures 8(a) and (b) show the effect of increasing both the accelerating and charging chamber fields on beam intensity. The influence of the accelerating field on intensity is substantial and due, in part, to beam focusing effects. This

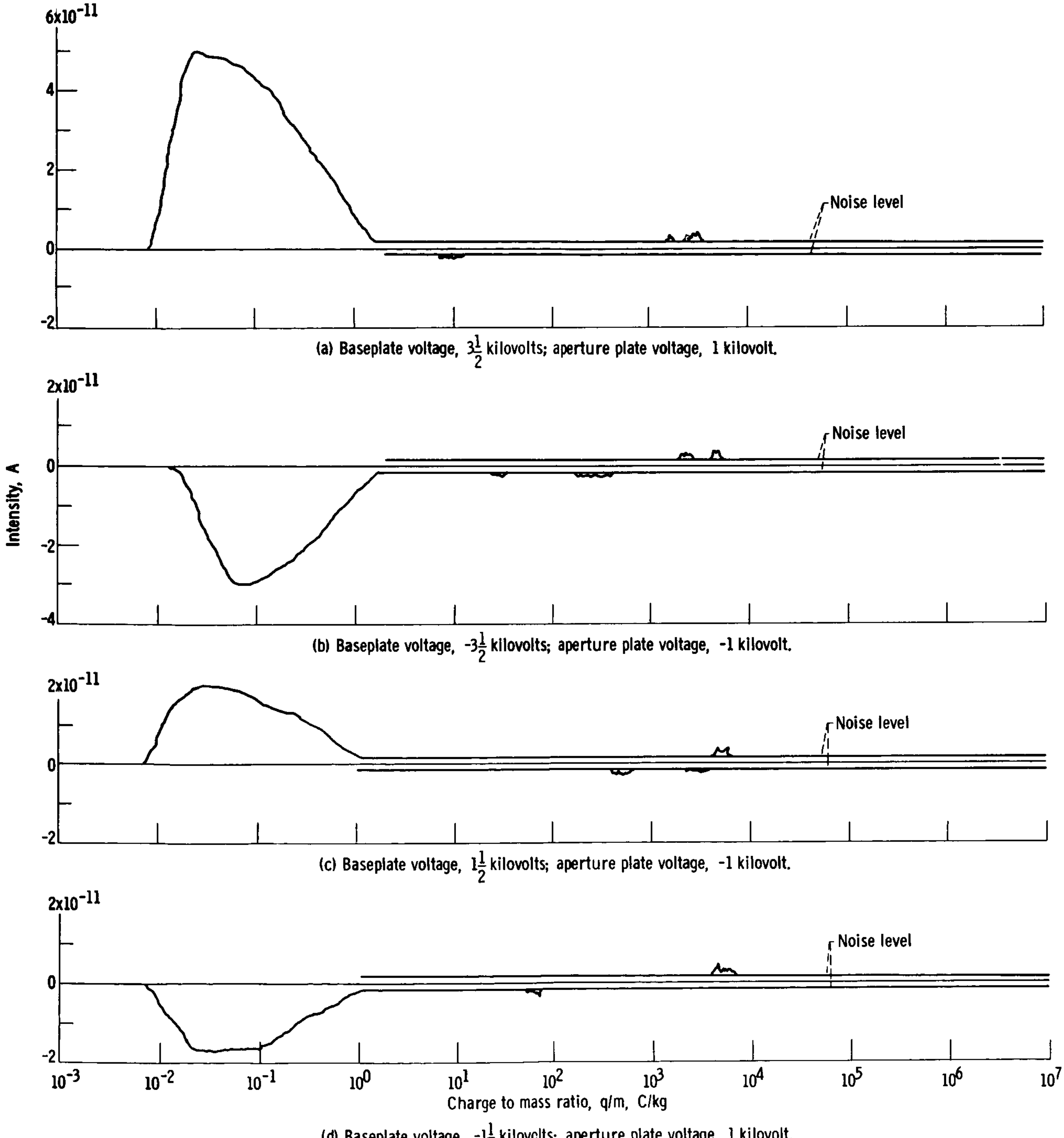
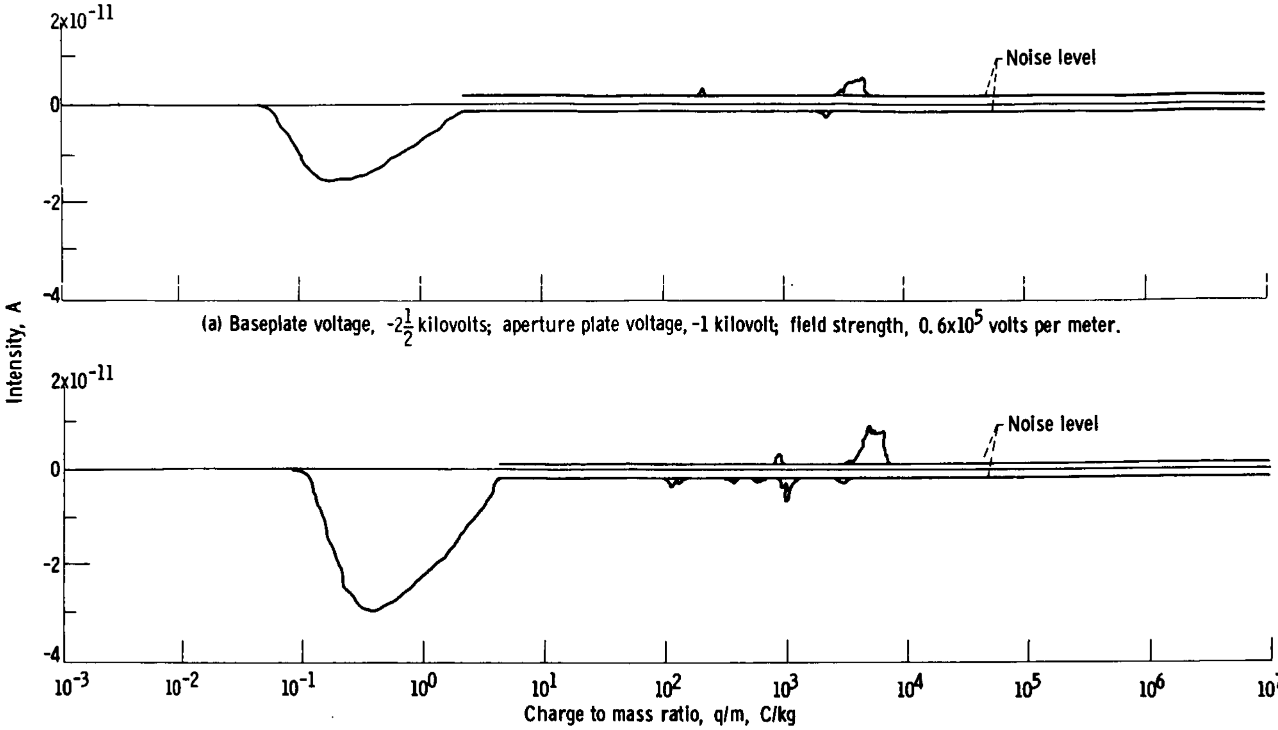


Figure 6. - Experimental charge-to-mass ratios for preformed submicron carbon powder at charging chamber field strength of 10^5 volts per meter and various baseplate and aperture plate voltages.



(a) Baseplate voltage, $-2\frac{1}{2}$ kilovolts; aperture plate voltage, -1 kilovolt; field strength, 0.6×10^{5} volts per meter.

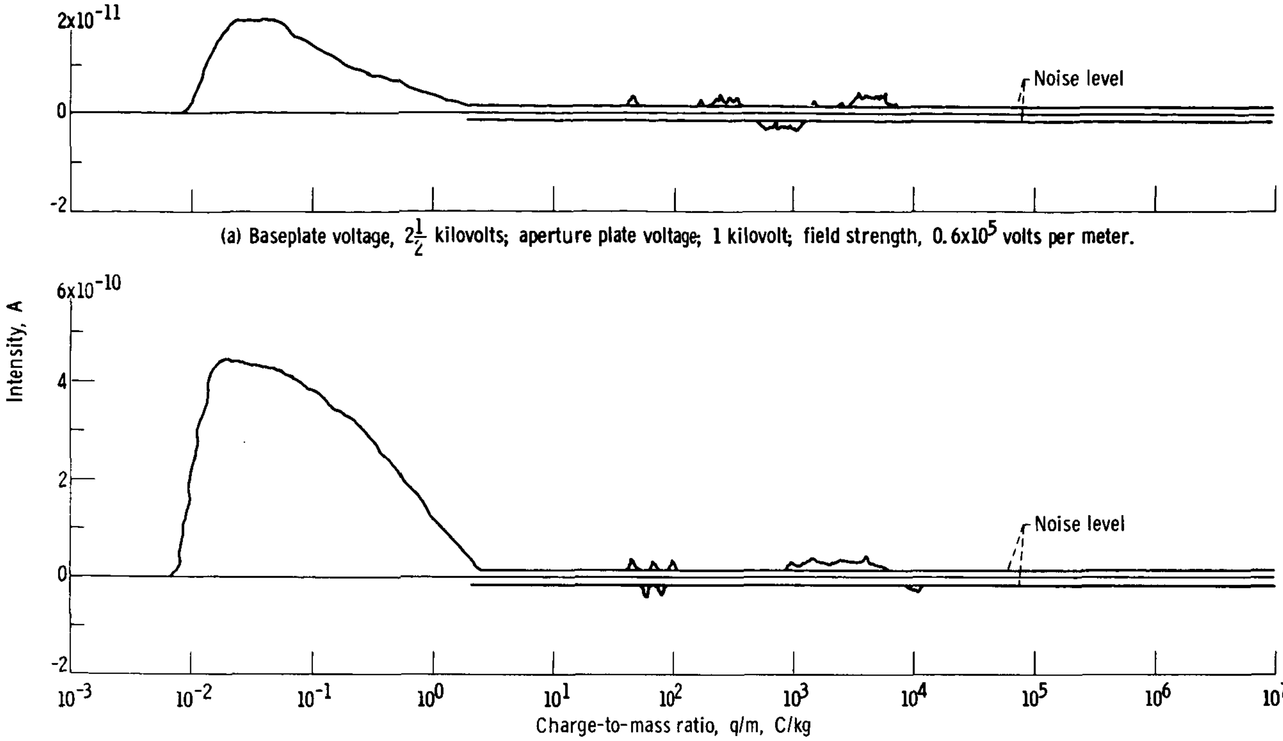
(b) Baseplate voltage, -4 kilovolts; aperture plate voltage, -1 kilovolt; field strength, 1.2×10^{5} volts per meter.

Figure 7. - Experimental charge-to-mass ratios for preformed submicron carbon powder for aperture plate voltage of -1 kilovolt and increasing baseplate voltage and negative field strength.

was determined from observing changes in the amount of carbon deposited in a Faraday collector during additional tests.

Comparison With Theory

Low charge-to-mass species. - From an examination of the quadrupole data, it is evident that the major mass fraction of the beam is carried by the low charge-to-mass species of carbon particles. The polarity of the low charge-to-mass species is as would be expected if charging were by induction charging. Comparison of figure 5 with the experimental results presented in figures 6 and 7 shows that the calculated peak charge-to-mass ratios for an agglomerate density are in closest agreement with the experimentally determined values. The experimental results show a much wider charge-to-mass distribution, however, than would be expected from figure 5. The wider distribution is possibly due to particle charging characteristics not considered in the derivation of equation (1). In that derivation it was assumed that, under the influence of an externally applied electric field, a conducting particle in contact with an electrode will accumulate charge q until the particle-field cancels the applied field (maintained between the



(a) Baseplate voltage, $2\frac{1}{2}$ kilovolts; aperture plate voltage; 1 kilovolt; field strength, 0.6×10^5 volts per meter.

(b) Baseplate voltage, $11\frac{1}{2}$ kilovolts; aperture plate voltage, $8\frac{1}{2}$ kilovolts; field strength, 1.2×10^5 volts per meter.

Figure 8. - Experimental charge to mass ratios for preformed submicron carbon powder for increasing baseplate voltage, aperture plate voltage, and positive field strength.

charging electrodes) which penetrates the agglomerate. However, the actual charge on the particle may be less than predicted if the particle leaves the charging surface before the maximum charge q has accumulated. This could happen because of the electrostatic force on the particle. Because of the nature of the charging process, the powder within the charging chamber is in rapid oscillation. The combined effect of collisions with the electrodes and with other particles will bring about some deagglomeration. This deagglomeration, together with the imperfect nature of the charging process, could lead to particles with a charge-to-mass ratio less than that theoretically predicted. On the other hand, the agglomerates are nonspherical and some may acquire a slightly higher charge-to-mass value than spherical particles because of field enhancement. These effects could produce the observed wider charge-to-mass distribution.

As the field in the charging chamber is increased, the average charge-to-mass values of the major peaks should increase as predicted by calculation of induction charging (eq. (1)). The actual field, however, may be that calculated from the potential difference existing between the aperture plate and the top surface of the powder. This value is about twice that of the charging chamber field, for the assumption of no powder in the chamber. Unfortunately, any trend toward increased charge-to-mass values is obscured by the scatter in the data, some of which occurs because of the varying amount of powder in the charging chamber throughout a test. Cho (ref. 7), however, using a somewhat different system and micron size particles, was able to detect a charge-to-mass increase with an increase in field, as theoretically predicted.

High charge-to-mass particle species. - The charged particles observed in the tests in the 10^{-1}- to 10^{4}-coulomb per kilogram range cannot be accounted for by contact charging alone. As outlined previously, electrostatic breakup of individual particles from the agglomerate could lead to particles exhibiting a high charge-to-mass value, and the low intensity peaks noted may have been the result of this factor alone. The observed polarity shift cannot be explained at this time. It is true that an increase in the magnitude of particle charging over that predicted by induction charging (eq. (1)) might be expected because of field enhancement at the surface of the nonspherical particle. However, field enhancement is dependent primarily upon particle geometry and orientation. Considering the shape of the agglomerated particles (fig. 2(a)), field enhancement factors much greater than an order of magnitude would not be expected in the tests herein. This is postulated in view of the fact that the quadrupole data taken at 10^{5} volts per meter yielded average charge-to-mass ratios in reasonable agreement with the predictions of induction charging with only a slight field enhancement effect. If the system had been operated at higher applied field strengths, for example 10^{7} volts per meter, and if it is assumed that the induction charge acquired by the particle varied linearly with applied field (ref. 7), the average charge-to-mass ratio of the particles would not be expected to be greater than 10 coulombs per kilogram.

Application to Colloidal Thrustor

The overall efficiency of a colloidal thrustor is a product of the power efficiency and the utilization efficiency. As described in reference 12, an important factor in determining the power efficiency is the distribution efficiency. The utilization efficiency for preformed powders might be expected to be high. That is, it may be possible to construct a charging chamber system such that a negligible neutral propellant flow rate would occur. Utilization efficiency was not a key factor in the tests discussed herein. The distribution efficiency, however, is an important factor for which meaningful values were determined from the tests.

From the complete charge-to-mass spectra shown in figures 6(a) to (d), the distribution efficiency was calculated, by a method similar to that presented in reference 12, to be 73 to 92 percent. If only the high intensity, low charge-to-mass ratio peak is included, the distribution efficiency is between 96 and 97 percent. In either case the distribution efficiencies are high enough to be useful. However, the predominant values of charge-to-mass ratio from the tests were less than 10^{-1} coulomb per kilogram. A very unrealistic thrustor accelerator potential of nearly 2.0×10^8 volts would be required to obtain a specific impulse level of 2000 seconds with these charge-to-mass ratios. Increasing the contact charging potential from 10^5 to 10^7 volts per meter may increase the average charge-to-mass ratio of the beam from 10^{-1} to approximately 10^1 coulombs per kilogram, as previously discussed. However, unless some different phenomena appear at high electric fields, this charge-to-mass ratio is still inadequate for colloid thrustor application. It is possible, of course, that supplementary charging methods, such as electron bombardment (ref. 9), may enhance the deagglomeration phenomenon and yield appropriate charge-to-mass ratios. However, such systems would introduce additional power losses. For example, Peterson (ref. 8) has calculated the power efficiency for electron-bombardment charging of preformed particles to be as low as 2.3 percent.

CONCLUSIONS

In this experimental investigation, charging of preformed submicron carbon powder has been examined for its possible application to colloidal thrustors. The carbon powder was charged by means of a parallel plate contact charging system, and the resultant beam was analyzed by means of a quadrupole mass filter. The charge-to-mass distribution, even in the comparatively simple system described herein, was found to encompass such a wide range of values that the quadrupole mass filter used for obtaining the data was an essential instrument.

Although the distribution efficiency was found to be high, contact charging in a parallel plate system does not appear to provide the proper charge-to-mass ratio for a useful colloidal thrustor system by at least four orders of magnitude. Extrapolating the results, by considering charging fields two orders of magnitude above those used in the tests (and above those usually encountered in ion thrustors), indicated some improvement in average charge-to-mass ratio was possible; however, this improvement is still not sufficient to be of interest for propulsion.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 21, 1966,
120-26-02-06-22.

APPENDIX - SYMBOLS

E_o applied field between charging chamber electrodes, volts/m

m ion or colloid mass, kg

q induced charge, C

r radius of powder, m

t time, sec

U applied d. c. voltage, volts

V applied RF voltage, volts

ϵ_o permittivity of free space, F/m

Φ potential of quadrupole focusing field, volts

ω angular frequency of applied electric field, rad/sec

REFERENCES

1. Mickelsen, William R.: Comparative Performance of Electrostatic Rocket Engines. Paper No. 62-74, Institute of Aero/Space Sciences, Jan. 1962.
2. Kuhn, William E.; Lamprey, Headlee; and Sheer, Charles, eds.: Ultrafine Particles. John Wiley and Sons, Inc., 1963.
3. DeBoer, J. H.: Atomic Forces and Adsorption. Advances in Colloid Science. Vol. III. H. Mark and L. J. W. Verwey, eds., Interscience Publ., Inc., 1950, pp. 1-63.
4. Jamba, D. M.: Heavy Particle Propulsion Research. Rept. No. RMD-1155-S3, Thiokol Chem. Corp., Reaction Motors Div., Apr. 1960.
5. Vedder, James F.: Charging and Acceleration of Microparticles. Rev. Sci. Inst., vol. 34, no. 11, Nov. 1963, pp. 1175-1183.
6. Cho, Alfred Y.: Research in Electrical Phenomena Associated with Micron Size Particles. Rept. No. 21 TR-005, Goodrich High Voltage Astronautics, Inc., May 8, 1962.
7. Cho, A. Y. H.: Contact Charging of Micron-Sized Particles in Intense Electric Fields. J. App. Phys., vol. 35, no. 9, Sept. 1964, pp. 2561-2564.
8. Peterson, Carl R.: Feeding, Deagglomerating, and Charging Solid Particles for Colloid Propulsion. PhD Thesis, Massachusetts Inst. Tech., 1963.
9. Harris, S. P.: Research on Charged Colloid Propulsion. Summary Rept. (NASA CR-54192), Rocket Power, Inc., Feb. 1, 1965.
10. Hunter, R. E.; and Wineland, S. H.: Charged Colloid Generation Research. Paper Presented at the Space Electronic Symposium, Los Angeles, May 25-27, 1965.
11. Paul, W.; Reinhard, H. P.; and Zahn, U. von: The Electric Mass Filter as a Mass Spectrometer and Isotope Separator. AEC TR-3484, 1958.
12. Norgren, Carl T.; Goldin, Daniel S.; and Connolly, Denis J.: Colloid Thrustor Beam Analysis: Design and Operation of a Suitable Quadrupole Mass Filter. NASA TN D-3036, 1965.
13. Rumpf, H.: The Strength of Granules and Agglomerates. Agglomeration, William A. Knepper, ed., Interscience Publishers, Inc., 1962, pp. 379-418.
14. Lowe, H. J.; and Lucas, D. H.: The Physics of Electrostatic Precipitation. British J. App. Phys., Suppl. No. 2, 1953, pp. S40-S47.

15. Overbeek, J. Th. G.: Phenomenology of Lyophobic Systems. Irreversible Systems. Vol. 1 of Colloid Science, Hugo R. Kruyt, ed., Elsevier Publ. Co., 1952, p. 60.

16. Dyke, W. P.; Trolan, J. K.; Martin, E. E.; and Barbour, J. P.: The Field Emission Initiated Vacuum Arc. I. Experiments on Arc Initiation. Phys. Rev., vol. 91, no. 5, Sept. 1953, pp. 1043-1054.

17. Müller, Erwin W.: Field Desorption. Phys. Rev., vol. 102, no. 3, May 1, 1956, pp. 618-624.

18. Germain, C.; and Rohrbach, F.: Mechanism of Breakdown in a Vacuum. Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris, 1963, vol. 2, pp. 111-117. (Also available as AEC-TR-6341.)

19. Alpert, D.; Lee, D. A.; Lyment, E. M.; and Tomaschke, H. E.: Vacuum Breakdown for Broad Area Tungsten Electrodes. Proceedings of the International Symposium on Insulation of High Voltages in Vacuum, Boston, Mass., Oct. 19-21, 1964, pp. 1-12.

NASA-Langley, 1966 E-3487

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